

Chapter 4. Underwater noise produced by the piling activities during the construction of the Belwind offshore wind farm (Bligh Bank, Belgian marine waters)

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Abstract

The piling of 56 foundations for 55 windmills and one offshore platform at the Blighbank (Belgian part of the North Sea, BPNS) has been surveyed for underwater noise. Maximum peak Sound Pressure Levels (SPL) up to 196 dB re 1 μ Pa were recorded at 520 m from the piling location. The extrapolated apparent source SPL was estimated at 270.7 dB re 1 μ Pa (95% CI: 260.4 – 281.1 dB re 1 μ Pa), although such an extrapolation of the measured levels to the near field (< 100 m) environment should be interpreted with care.

It is confirmed that the underwater noise level is a reason for concern, at least for marine mammals such as porpoises, seasonally abundant around the construction area. It is however very difficult to quantify and qualify the effects of the increased underwater noise level on components of the ecosystem, and a continued effort to do so is needed. To fine tune our estimates of noise propagation in the bathymetrically complex BPNS, in future more attention will be paid to the attenuation characteristics of underwater noise.

Samenvatting

Tijdens het heien van 56 funderingen voor 55 windmolens en 1 offshore platform op de Bligh Bank (Belgisch deel van de Noordzee, BDNZ), werd het geproduceerde onderwatergeluid onderzocht. Maximale piek geluidsdruk niveaus (SPL) tot 196 dB re 1 μ Pa werden gemeten op een afstand van 520 m van de heillocatie. Door extrapolatie werd het SPL ter hoogte van de bron geschat op 270.7 dB re 1 μ Pa (% CI: 260.4 – 281.1 dB re 1 μ Pa). Dergelijke extrapolaties van de gemeten niveaus naar de SPL in de nabijheid de bron (< 100 m) moeten echter met enige voorzichtigheid geïnterpreteerd worden.

Onderwatergeluid is een bezorgdheid wegens de mogelijks schadelijke impact op zeezoogdieren zoals de bruinvis, die seizoenaal abundant voorkomt in het constructiegebied. Het is echter bijzonder moeilijk om de effecten van het verhoogde onderwatergeluid op bepaalde componenten van het mariene ecosysteem te kwantificeren en te kwalificeren. Verdere inspanningen om dit te kunnen doen zijn nodig. Om de schattingen van de propagatie van onderwatergeluid in het bathymetrisch complex BDNZ te verbeteren, zal er in de toekomst meer aandacht worden besteed aan de attenuatie karakteristieken van onderwatergeluid.

4.1. Introduction

The main objective of the measurements of underwater noise in the construction and operational phases of offshore wind farms is to assess possible impacts on biota. Recent investigations have indicated that the environmental impact of anthropogenic underwater noise can be important in general (e.g. OSPAR 2009a, 2009b), while the activity of greatest concern is pile driving during the construction phase of the projects (Bailey *et al.*, 2010; Gordon *et al.*, 2009; OSPAR 2008, 2009a, 2009b). Indeed, this activity produces very intense underwater noise, with a level potentially directly affecting biota such as marine mammals, cephalopods and fish larvae (Finneran *et al.* 2005; Kastak *et al.* 2005; Lucke *et al.* 2009; Madsen *et al.*, 2006; Nachtigall *et al.*, 2003; Prins *et al.*, 2009; Richardson *et al.*, 1995; Thomsen *et al.*, 2006). Human generated noise is now considered an important form of pollution and marine managers and policy makers are aware of the environmental impact anthropogenic underwater noise may have. This is for instance demonstrated by its coverage by international agreements and conventions, such as in the framework of the European Union¹, the Convention on Migratory Species² and ASCOBANS³. As such, the underwater noise of offshore wind

¹ Marine Strategy Framework Directive; Directive 2008/56/EC

² CMS Resolution 9.19 on adverse anthropogenic marine/ocean noise impacts on cetaceans and other biota, adopted by the 9th Meeting of the Conference of the Parties

³ Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas: Resolution on adverse effects of underwater noise on marine mammals during offshore construction activities for renewable energy production, adopted at the Meeting of the Parties 6.

farm related activities remains an important issue of the wind farm monitoring programme in Belgian waters.

Considering the wind farm area in the Belgian part of the North Sea (BPNS), Haelters *et al.* (2009) quantified the mean background underwater sound pressure level (SPL) at the Belwind location, prior to the construction activities, and during weather conditions with wind force < 3 Bft and seastates < 3, at around 95 to 100 dB re 1 μ Pa for frequencies ranging between 10 Hz and 2 kHz. Various wind farm related activities during the construction and operation phase add to the underwater noise. Especially piling activities are considered to be of concern in relation to the increases of the underwater noise levels. The effects on harbour porpoises of increases in underwater noise due to piling can be death or injury (permanent or temporary hearing threshold shift; respectively PTS and TTS) close to the sound source, and an avoidance reaction and masking of the porpoise sonar further away (Bailey *et al.*, 2010, Lucke, 2010; Southall *et al.*, 2007).

This paper aims at (1) the quantification of the SPL generated by piling activities at different distances from the piling location, (2) a spectral analysis of the noise and (3) an extrapolation of the measured SPL to the apparent source SPL and to the distance at which a background SPL is reached.

4.2. Material and methods

The measurement protocol, as used for previous underwater noise measurements (see Haelters *et al.*, 2009) was used for the present study; it is summarised below. It was however slightly adapted in view of the different characteristics of piling noise: shorter measurements (of around 2 minutes each) allowed for measurements of noise during piling activities over a large range of distances (400 m to 14 km from the piling location).

4.2.1. Measurement methodology

As a platform for the measurements we used the Tuimelaar, a rigid inflatable boat (RIB) owned by the RBINS-MUMM. All instruments possibly interfering with the noise measurements were turned off during recording. For each recording, the RIB was left adrift from a predefined position with the engines shut off. The position of the RIB was registered automatically every five seconds by a GARMIN GPSMAP 60 Cx. At the beginning and the end of each measurement a reference signal was recorded. The clock of the recorder was synchronised beforehand with the GPS-time (UTC).

A proper and (near) real time communication between the piling operator and the measuring team on when exactly the piling will take place, proved to be a very delicate aspect for the planning and implementation of the measurement campaigns. As such, many planned or ongoing campaigns were cancelled or interrupted due to changes in the piling procedure and timing. An overview of the successful campaigns is presented in Table 1.

Table 1. Metadata of the underwater noise measurements at the Belwind site on the Blighbank: monopile A02 (September 26th, 2009) and monopile B10 (January 15th, 2010).

26th September 2009 (monopile A02)			
Position start recording		Distance (m)	Energy/Blow (kJ)
Latitude	Longitude		
51°40.39'	2°50.03'	~3000	~590
51°39.41'	2°50.64'	~4820	~760
51°38.25'	2°51.25'	~6990	~875
15th January 2010 (monopile B10)			
Position start recording		Distance (m)	Energy/Blow (kJ)
Latitude	Longitude		
51°34.59'	2°57.31'	~14150	~710
51°37.58'	2°52.89'	~7250	~940
51°38.61'	2°51.58'	~5500	~950
51°38.55'	2°50.29'	~4000	~960
51°38.45'	2°49.04'	~2580	~960
51°38.52'	2°48.16'	~1580	~970
51°38.60'	2°47.41'	~680	~970
51°38.56'	2°47.41'	~700	~980
51°38.50'	2°47.44'	~770	~970
51°38.55'	2°47.24'	~520	~990
51°38.52'	2°47.32'	~630	~970

4.2.2. Acoustic measurement equipment

At every occasion, one Brüel & Kjær hydrophone (type 8104) was deployed at a depth of 10 m. A Brüel & Kjær amplifier (Nexus type 2692-0S4) was placed between the hydrophone and the recorder in order to allow for an amplification of the signal. A reference signal is used to calibrate the signal. The signal is recorded using an audio MARANTZ Solid State Recorder (type PMD671). It was operated with the highest possible sampling rate of 44.100 Hz. The signal was recorded in WAVE format (.wav) on Compact Flash cards of 2 GB (Sandisk Ultra II). All equipment was powered by batteries.

Before the 2009 measurements started, the complete instrumentation chain, except the data recorder, was calibrated by the manufacturer Brüel & Kjær.

4.2.3. Analysis of the recordings

A spectral analysis of the signal in the form of the third octave band spectrum of the underwater Sound Pressure Level (SPL) is presented. The spectra were computed using a routine built on MATLAB and according to the norm IEC1260. The maximum peak SPL at the measuring stations, located at different distances from the piling site, are provided, together with a simple linear model allowing for an extrapolation of this SPL at distances, at which no measurements were available, including to the apparent source SPL (at 1 m). This extrapolation should be treated with care, taking into account the complex bathymetry of the BPNS (cf. far field extrapolation) and the complexity of the near field noise generation.

4.2.4. Piling activity details

For the piling of the 56 monopile foundations at the Blighbank (at a depth of 10 – 24 m MLLWS – Mean Low Low Water Spring), a hammer IHC hydrohammer S1200, operated from the support vessel Svanen, was used. The hammer features a maximum power of 1200 kJ. The average energy used for each stroke however was 705 kJ (range: 526-965 kJ) (Table 2). The length of the monopiles ranged from 47 m to 65 m, and the outer diameter was 4 m at the top and 5 m at the lower part. The

number of hammer blows needed to drive each monopile 18 to 37 m into the seabed was 1841 to 4811 (average: 2981). It took 112 h of piling to put the 56 monopiles in place.

In this report, the piling of the monopiles A02 and B10 is described. For a similar penetration depth (29 and 28 m) and a mass above the average (400 and 452 t), the piling of A02 and B10 showed a very different piling duration: 64 minutes for A02 versus 162 minutes for B10. Also the total energy used during pile driving was different: it was close to the minimum value for A02 (1.4 GJ) and it was the highest value for B10 (3.2 GJ). As such, both monopiles are illustrative for the variation in monopile characteristics and piling activities of the Belwind project phase 1.

Table 2. Summary statistics of the piling activities of monopiles A02 and B10, targeted in this study, as well as the averages, minima and maxima encountered for the 56 monopiles of Belwind phase 1 (source: Belwind).

Piling activities during Belwind phase 1						
	Unit	A02	B10	Average	Min	Max
Pile length	m	54	63	54	40	65
Mass	t	400	452	375	254	509
Number of strokes required		2114	3848	2982	1814	4811
Average energy per stroke	kJ	641	837	705	526	965
Duration of piling	min	64	162	120	64	233
Penetration	m	29	28	27	18	37
Total energy	GJ	1.4	3.2	2.1	1.38	3.2

4.3. Results

The acoustic pressure measured at 4.8 km from the piling location of monopile A02 reaches a maximum amplitude of about 700 Pa (Figure 1). A 0.35 s zoom into one single stroke shows the noise generated by a single stroke to last for about 0.25 s (Figure 2).

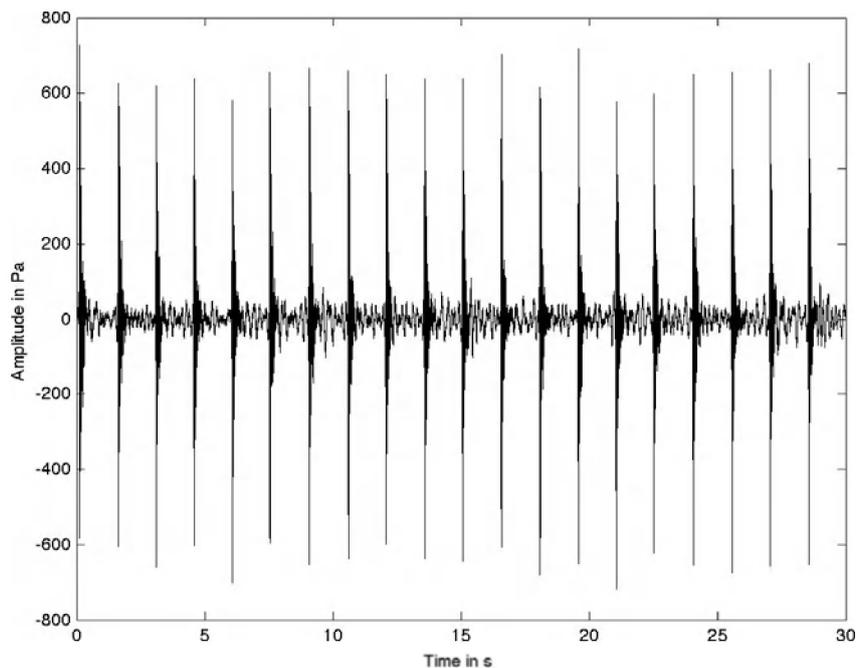


Figure 1. Amplitude of the acoustic pressure, produced by 20 piling strokes of 760 kJ and recorded at 4.8 km from the piling of the A02 monopile.

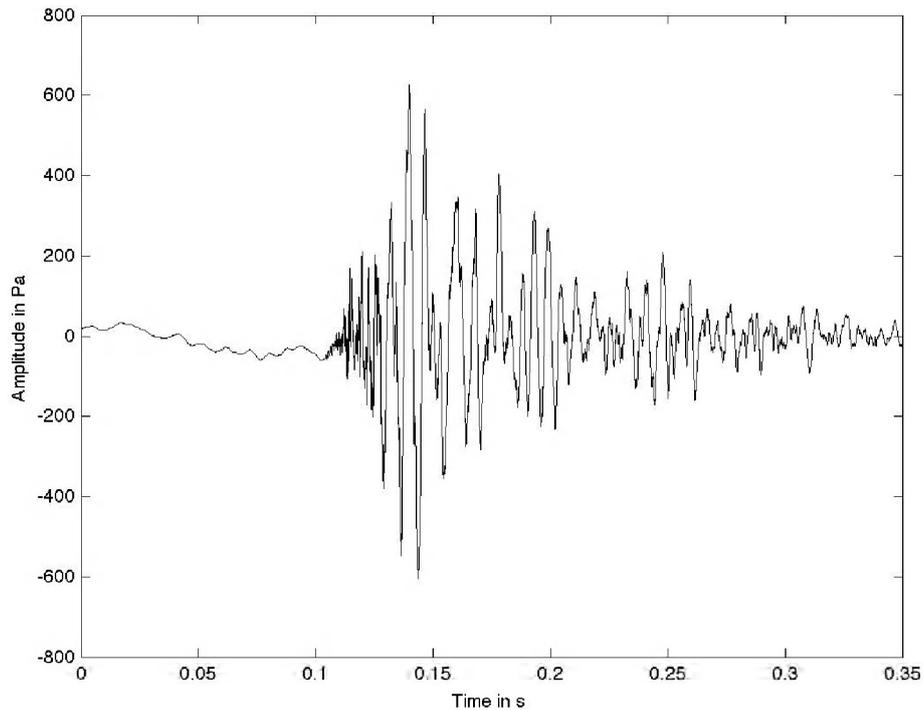


Figure 2. Acoustic pressure of a 0.35 s zoom into one stroke as taken from figure 1.

The spectral analysis of the underwater noise, produced by the piling of monopile A02 and recorded at 3 km from the source, shows a maximum amplitude of about 150 dB re 1 μ Pa between 100 Hz and 200 Hz, as well several secondary peaks (Figure 3). Most of the energy is found between 50 Hz and 1 kHz. The recording at 770 m from the monopile B10 (Figure 4) shows a similar pattern, with a maximum sound pressure level of about 160 dB re 1 μ Pa at a frequency of 150 Hz. In both examples presented, the SPL decreased with distance.

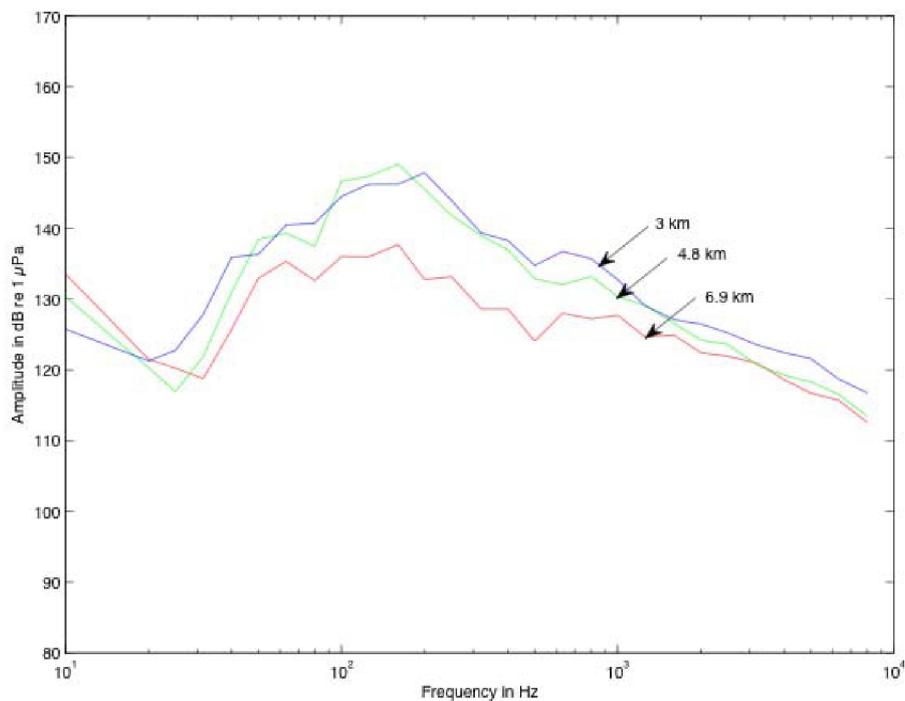


Figure 3. 1/3 octave spectrum of the underwater noise recorded during the piling of monopile A02 at three distances from the piling location.

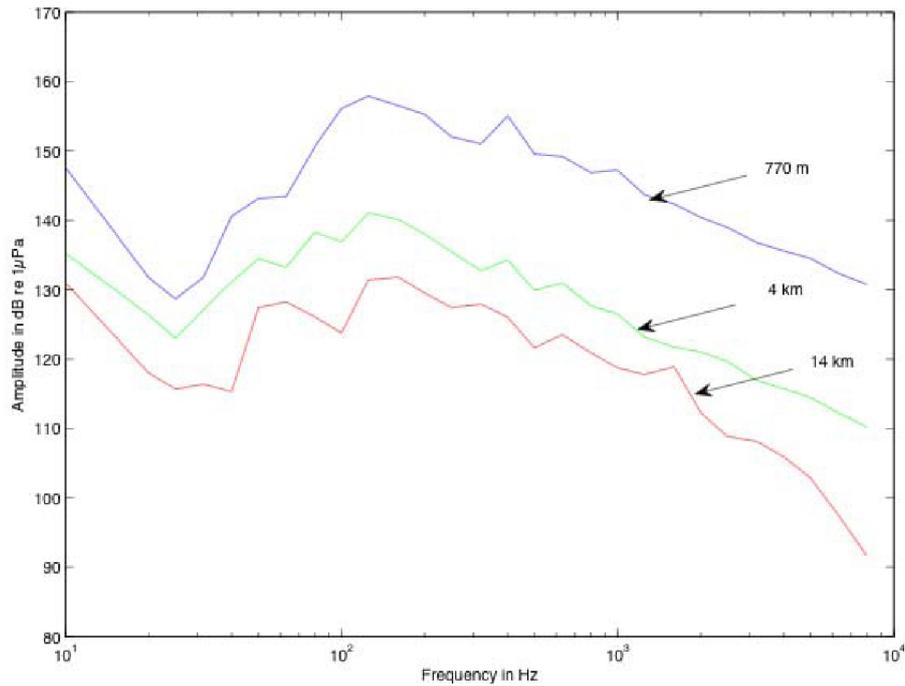


Figure 4. 1/3 octave spectrum of the underwater noise recorded during the piling of monopile B10 at three distances from the piling location.

The piling of monopile A02 showed a maximum peak SPL ranging from 166 dB re 1 μ Pa at 7 km to a maximum of 177 dB re 1 μ Pa at 3 km distance. Values measured for monopile B10 ranged from 160 dB re 1 μ Pa at 14 km from the pile to 196 dB re 1 μ Pa at 560 m.

Table 3 Maximum peak SPL and energy per blow during the measurements at different distances from the source (see Table 1).

Distance to A02 (m)	Maximum peak sound pressure level amplitude (dB re 1 μ Pa)	Energy/Blow (kJ)
~6990	166	~870
~4820	177	~760
~3000	177	~590
Distance to B10 (m)		Energy/Blow (kJ)
~14150	160	~710
~7250	165	~940
~5500	169	~940
~4000	168	~960
~2580	174	~960
~1580	185	~970
~770	193	~970
~700	193	~980
~680	192	~970
~630	195	~970
~520	196	~990

The energy used per blow showed a high variability for the piling of A02, while a more constant figure, except for the recording taken at 14 km, was observed for monopile B10 (Table 3). As such, an

extrapolation of the relationship between SPL and distance could be attempted only for the piling of B10 (Figure 5).

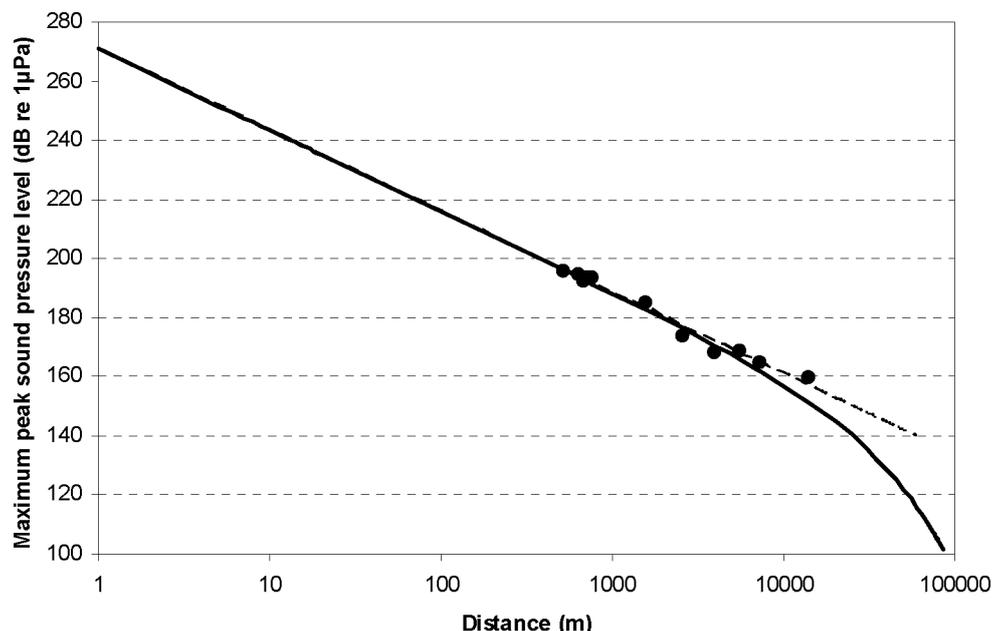


Figure 5. Relationship between maximum peak SPL (dB re 1 μ Pa) and distance (m) from the source of the underwater noise during the piling of monopile B10. The dashed line represents the fitted linear model of the measured values (closed circles). The solid line represents the maximum peak SPL as a function of distance, taking into account both attenuation and absorption.

The regression model (Maximum peak SPL = $-27.4 \log(d) + 270.7$ dB), in which d is the distance to the source, features a transmission loss of $27.4 \log(d)$ (95% CI: 30.5 to 24.3 $\log(d)$). The intercept of the linear regression model at a distance of 1m from the source is estimated at 270.7 dB re 1 μ Pa (95% CI: 260.4 - 281.1 dB re 1 μ Pa). Using the same linear model, the distance at which a background SPL during good weather conditions of 105 dB re 1 μ Pa is reached, was found to range from 100 to 500 km, with a 95 % confidence interval of 79 - 630 km. However, a more complex model, taking account of the transmission loss (i.e. attenuation) of $27.4 \log(d)$ and an absorption coefficient of 0.0004 dB/m (cfr. Bailey *et al.*, 2010), predicts the distance at which the noise could still be distinguished from background noise at 79 km.

4.4. Discussion

4.4.1. Underwater noise sound pressure level, produced by piling activities

The underwater noise level produced by piling (up to 196 dB re 1 μ Pa at 520m) is much stronger than the background noise or noise generated by shipping in the BPNS (up to 120 dB re 1 μ Pa; Haelters *et al.*, 2009), even at many km from its source, and therefore a reason for concern. Personal experiences (A. Norro) of this underwater noise during diving operations at 15 km distance from the piling location learned that the noise was annoying, but not harmful to the diver. At every stroke however, a shock wave (vibration) was clearly sensible to the divers.

The transmission loss models, as presented in Figure 5, are plausible for the SPL in the far field environment (i.e. > 100m from the source *sensu* Nedwell and Howell 2004). However, not taking into account absorption, our estimate based on the linear model is most likely overestimating the distance at which the noise could still be distinguished from background noise. Taking account of noise absorption on the other hand leads to an underestimation of SPL at our measurement point at 14 km distance, when the lowest blow energy (710 kJ) was used. As a consequence, at this moment our data

do not allow for a more precise estimate of the distance at which the noise could still be distinguished from background noise. However, it can reliably be stated that the noise could still be discriminated from the background noise at a distance of at least tens of kilometers. Such distance means that the underwater noise produced by piling activities is measurable within the whole BPNS and even within part of the marine environment of all our neighbouring countries. However, the estimate of this distance changes with the choice of the absorption coefficient, and will depend on several factors, an important one being weather conditions affecting the background noise level.

The use of the linear transmission loss model for the near field environment and hence the estimation of the SPL at the source, is further prone to many uncertainties, as the area close to the source is the seat of complex interactions between various components of the source, which in itself is not a point source. As such, the extrapolation is frequently not considered legitimate in the near field environment. The SPL estimate of 270.7 dB re 1 μ Pa (95 % CI 260.4 - 281.1 dB re 1 μ Pa) at 1 m from the source should be considered a rough indication of the apparent source SPL, and should be interpreted with care.

The difference in the form of the spectra, as observed between A02 and B10, could be explained by differences in e.g. the size of the monopile, the local sedimentary environment, the blow energy and the topographical position on the sandbank, each having a specific influence. For example, it should be noted here that our measurements were made with a sand ridge between the source and the hydrophone, which can strongly affect both the propagation and the attenuation of the underwater noise (Urick, 1983; Lurton, 2002; Medwin, 2005).

While a standardisation of measuring, analysing and expressing underwater noise is considered necessary, and is being developed (de Jong *et al.*, 2010; EU, 2010), this standardisation is still at an early stage of acceptance and general use. Although the current lack of standardisation has to be taken into account when comparing our measurements with those from other studies, such comparison can already shed a light onto the major commonalities of underwater noise, produced by offshore wind farm piling activities. At the Barrow site in the U.K., for instance, Nehls *et al.* (2007) found a maximum peak SPL of 193 and 199 dB re 1 μ Pa normalized at 500 m from the piling of a monopile with a diameter of 4.7 m (stroke energy unknown), which is highly similar to the 196 dB re 1 μ Pa measured in this study at 520 m from the piling of a 5 m-diameter monopile with stroke energy of 990 kJ. The spectral analysis, presented by Nehls *et al.* (2007), further revealed a similar maximum SPL at about 200 Hz, with a secondary peak at about 1 kHz. It should however be noted that the secondary peak observed in this study and by Nehls *et al.* (2007) is not always present, as demonstrated for the Q7 wind farm (the Netherlands) by de Jong *et al.* (2008a). In terms of amplitude of the spectra, Nehls *et al.* (2007) as well as de Jong *et al.* (2008a) presented figures of about 170 dB re 1 μ Pa at about 200 Hz for a similar distance of about 850 m. Our measurements were made further away, which explains the lower SPL values ranging from 150 to 160 dB re 1 μ Pa at 100-200 Hz. The importance of low frequencies (Figures 3, 4) were also observed by De Jong *et al.* (2008) and may result from a high energy stroke.

Our measurements of the increases in UW noise level have clearly demonstrated that they are a reason for concern for the environment. They clearly warrant the mitigation measures proposed in the EIA report (MUMM, 2007) and taken up in the license for construction. Some of the measures proposed prevent the exposure of sensitive species to excessive noise, such as the use of acoustic warning devices, the use of a ramp-up procedure, or the avoidance of piling operations during periods of the year with high numbers of porpoises present in the vicinity of the construction area. Other methods that are available or are being investigated in the framework of other offshore wind farm projects tackle the noise output itself; it has been demonstrated that the noise emitted is significantly lower when using methods such as bubble curtains around the piles, the use of a telescopic double wall steel tube, the use of inflatable sleeves, or the drilling of the piles instead of ramming (Nehls *et al.*, 2007; Nedwell and Brooker, 2008). Such measures and methods should be continued to be considered for future OWS projects in Belgian waters.

4.4.2. Impact on marine life, *in casu* marine mammals

Only few direct impact studies of pile driving on marine mammals have been made in the field. However, these studies have clearly demonstrated that effects can occur up to tens of kilometers from

the piling site. Some studies have investigated audibility to discomfort noise levels in marine mammals in captivity, including porpoises, bottlenose dolphins and seals (David, 2006; Kastelein *et al.*, 2005; Mooney *et al.*, 2009; Verboom & Kastelein, 2005). Such levels can be compared to actual noise levels measured during pile driving. In combination with baseline studies of the marine mammals occurring in the areas concerned, an assessment of a potential impact can be made.

Field studies using Porpoise Detectors (PoDs) during pile driving have indicated effects on porpoises (decrease in acoustic detections) up to (at least) 25 km from the pile driving site, and lasting for hours to days after each piling (Brandt *et al.*, 2009; Carstensen *et al.*, 2006; Diederichs *et al.*, 2009; Henriksen *et al.*, 2003; Tougaard *et al.*, 2003; 2005; 2009a; 2009b). Lucke (2010), who performed aerial surveys before and during pile driving, detected an absence of porpoises in an area of over 1000 km² (= radius of about 18 km) around a piling site during piling activities; before this activity, porpoises commonly occurred in the area. Several studies indicated that also during other construction activities the abundance of porpoises in the area had decreased (Brandt *et al.*, 2009; Carstensen *et al.*, 2006; Tougaard, *et al.*, 2006a; b).

Although many criteria for sound levels potentially leading to PTS and TTS for porpoises have been presented, none have been widely accepted. Difficulties remain in the lack of a standardised description of noise (De Jong *et al.*, 2010), and in the presentation of noise exposure in its different aspects: not only the absolute level (SPL, peak to peak) of noise is relevant for cetaceans, also the Sound Exposure Level (SEL) integrated over a single noise event and the cumulative exposure over time, such as exposure to repetitive pulses during pile driving (De Jong & Ainslie, 2009; Madsen, 2005;). Finally a frequency weighting of the sound cetaceans are exposed to can be applied, taking account of their audiogram; this means that it is weighted against the inverse shape of the audiogram, and in some cases is corrected also for the non linearity of intense sound loudness (Nedwell *et al.*, 2007; Southall *et al.*, 2007; Verboom & Kastelein, 2005). This better accounts for the loudness of a sound as experienced by marine mammals, but complicates matters more, given that the audiograms are different for each species, and are not well known for many.

Verboom & Kastelein (2005) have proposed, on the basis of experiments, dose-response relationships for porpoises; the severe discomfort level, TTS level and PTS level were respectively 125dBw, 137 dBw and 180 dBw re 1 μ Pa (dBw: weighted against the inverse shape of the audiogram of the porpoise). Southall *et al.* (2007) have calculated for PTS and TTS in 'high frequency cetaceans', amongst which Delphinidae, levels of 198 dBw respectively 183 dBw re μ Pa²s (weighted against a general audiogram for high frequency species and the non linearity of intense sound loudness). The US National Marine Fisheries Service (NMFS, 2003) has considered a limit for exposure for cetaceans of 180 dB re 1 μ Pa (rms), without a firm basis nor frequency weighting (in Nedwell & Brooker, 2009; Madsen *et al.*, 2006), while the German Federal Environment Agency (UBA) has defined, on the basis of studies by Lucke (2009), that a threshold of 160 dB re 1 mPa² s (SEL) and 190 dB re 1 μ Pa (SPL) should not be exceeded at 750 m from a piling site.

At the Blighbank construction site, the maximum peak SPL exceeded 192 dB re 1 μ Pa up to around 800 m from the source; at 14 km it was 160 dB re 1 μ Pa, and an extrapolated noise level at a distance of 20 km would be 144 dB re 1 μ Pa. While it was not possible to make direct observations of impacts during the pile driving at the Blighbank, the observed increases in underwater noise level were similar to those measured in other studies (Betke, 2010; De Haan *et al.*, 2007; Nedwell *et al.*, 2004; Nedwell & Howell, 2005; Nedwell & Brooker, 2009; Tougaard *et al.*, 2009; overview in Bloor, 2009). The measured levels cannot readily be interpreted into distances for TTS and PTS levels in porpoises. However, comparing the source level to the source level measured at other piling sites, and the observed effects, it is likely that effects on porpoises occurred up to at least 25 km from the sound source. The noise would have been audible for porpoises at a larger distance, but it is not clear if this has effects. It cannot be expected that PTS would have occurred in some animals, given the presence of noisy vessels at the site before pile driving - already considered as a 'ramp-up procedure' in itself by Leopold & Camphuysen (2009), and the use of an alerting device half an hour before the start of pile driving, preventing injury in the form of PTS or TTS. However, for a similar piling at the Q7 offshore wind farm, De Jong & Ainslie (2008b) estimated that the noise level was well above the discomfort threshold up to 5.6 km from the piling site (the largest distance at which noise was measured), and that at distances closer than 500 m the levels were higher than the TTS criterion as established by Verboom & Kastelein (2005). Gordon *et al.* (2010) have proposed a model in which

the SEL is assessed against the swimming speed of porpoises and proposed TTS and PTS levels, and have concluded that even with pingers or deterrent devices, porpoises may still suffer PTS up to several kilometres from piling sites. Bailey *et al.* (2010) estimated that TTS or PTS could only occur within 100 m from a piling site (piles of 1,8 m diameter, blow energy 510 kJ), while strong avoidance reactions would occur within 20 km from the piling site.

The number of porpoises disturbed by the pile driving at the Blighbank site was probably limited, given the relatively low densities of porpoises present in this period of the year (Haelters *et al.*, this volume). Presuming a discomfort effect at a distance of 25 km (on the basis of Brandt *et al.* 2009; Diederichs *et al.* 2009; Tougaard *et al.* 2009a), and a density of porpoises of 0.2 animals/km², it can be calculated that 400 porpoises could have been disturbed. With densities of over 1 porpoise/km², as observed in Belgian waters during late winter and early spring (Haelters, 2009), more than 2.000 animals would be disturbed. However, there is only limited knowledge on the seasonal abundance of porpoises in this area, and it is fairly unpredictable. Also, the baseline monitoring of porpoises focuses on Belgian waters, which only partly cover the area possibly impacted.

4.4.3. Future adaptations to the monitoring strategy

Further developments are needed to better investigate the attenuation of underwater sound in a complex bathymetrical environment, such as the BPNS with its numerous sand ridges and a sandbank-swale morphology. It is hence advised to have measurements of the same (piling) event at the same time at different locations. This could be achieved using a moored instrument or a second survey team on a different position. Given the bathymetrical complexity of the BPNS, these measurements should account for geomorphologic privileged directions. Consequently, the underwater noise measurements of the next phase of piling activities should be executed in an along-bank, as well as a cross-bank configuration. Also, noise measurements should be expanded to both shorter and longer distances from the source as the ones described in the current report.

Furthermore, more effort should be directed into concrete impact assessment of pile driving on harbour porpoises in Belgian waters (for more details: Haelters *et al.*, this volume). Agreed standards of noise measurement, analysis and expression, and a common adoption of the level at which PTS, TTS and discomfort occurs in harbour porpoises, would further be useful for a better assessment of the impact, including a cumulative impact at a population level due to the construction of several wind farms in the southern North Sea.

Furthermore, it is advised to be able to visualize the acquired signal and to compute the spectral analysis in real time. This would allow for a real time check for possible overloading of the acoustic signal and hence for an improved efficiency of the time at sea.

4.5. Conclusions and outlook

During this first phase of piling activity at the Blighbank, it has been shown that pile driving drastically increases the underwater noise level. At 520 m from the source a maximum peak SPL of 196 dB re 1 μ Pa was measured, with a piling blow energy of 990 kJ. The spectral analysis of the underwater noise showed a main peak between 100 Hz and 200 Hz and at about 1 kHz. Our measurements of amplitude and spectra agree well with other measurements of the underwater noise, produced by piling activities at other offshore wind farms.

The ecological consequence of the disturbance for porpoises and other animals such as fish and cephalopods remains unknown. For marine mammals it should be described as an impact on individual animals, up to impacts on a population level. Due to the piling activity at the Blighbank, the ecological impact on harbour porpoises would be that at least the foraging ability of a number of animals is temporarily impeded; they could be excluded from a preferred foraging area, and be driven to areas already used by competitors for food. Such effects can have an impact on the fitness of individual animals, and while this could be limited in the case of the construction of a single wind farm, cumulative effects will occur when many wind farms are constructed simultaneously or consecutively.

4.6. Acknowledgements

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4.7. References

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